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Analysis on reliability aspects of wind power

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ABSTRACT

The analysis on reliability aspects of wind power finds more significance as compared to that in conventional power generation systems. In spite of the intermittent and variable nature of wind energy, it can be usefully tapped to generate electrical power for meeting part of the energy demand of the population. The present paper undertakes an analysis on the reliable aspects of wind energy conversion system and applies to seven wind farms in Muppandal region in India. For the purpose of analysis, two reliability indices are used; one is coined as the period during which the expected wind energy is not supplied and the other one is the loss of load expectation index which analyzes the degree of matching of wind farm power generation with the load model. The study also investigates the effect of increasing the hub height of wind energy conversion systems.

Contents

1. Introduction

The assessment of the reliability of wind farms in generation systems is essential from the planning point of view. Researches on the improvement in performance of wind power plants are getting importance as its application is increased rapidly [1–3]. The wind turbine generators in a wind farm will not have a fixed capacity distribution, owing to the constant variations in the outputs of each wind turbine output despite all of them being fed from the same wind energy source. Hence, a wind energy conversion system cannot produce power at its rated capacity throughout the year. Due to the partial availability of wind generated power, the actual capacity value of a wind power plant in a utility system is relatively low, which is equivalent to the wind power plant's capacity factor multiplied by its rated capacity [4]. The relationship between the wind turbine power output and wind speed is non-linear and hence the power output characteristics of wind energy conversion system are different from that of any conventional generation systems. Even though wind energy is not consistent, wind power plants contribute to meet the energy demand requirements.

In recent years, wind energy based generation has witnessed an exponential growth in most developing countries. In India, several

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states have increased their wind energy penetration into the system grids to supplement the existing generation from conventional sources, namely, hydro and thermal options. It would appear that in view of the rapid growth of wind energy generation in India, this form of evaluation studies can help planners in understanding the scope, limitations and future of such systems in the Indian environment.

As actual field data is needed for the analysis of reliable aspects of wind power, it is necessary to obtain this data from wind farms in India. Field data collected from a set of seven wind farms in Muppandal region of Tamilnadu, India, are used in this study.

2. Description of wind farms taken for analysis

The state of Tamilnadu is in the southern region of India at latitude between 8° 5′N and 13° 35′N and longitude between 76° 15′E and 80° 20′E. The geographical location of the state of Tamilnadu is favourable for wind power development due to the presence of major mountain passes along the western border of the state. This state is ahead of other Indian states with more than 50% of the total installed wind energy capacity of India. Tamilnadu state has experienced an encouraging response from the private sector ever since the inception of wind power in the country. It has a total installed wind turbine capacity of 4906.74 MW, of which 4887.34 MW by the private sector and 19.4 MW in the form of government demonstration projects [5,6].

The Muppandal region in Tamilnadu has the distinction of having one of the largest concentrations of wind turbines at a single location. In this region, wind farms are spread along the national highway from Muppandal to Kanyakumari, at the confluence of the Bay of Bengal, Arabian Sea and the Indian Ocean. The Aralvaimozhi mountain pass strengthens the winds of South-West monsoon, which blow from May to September and reaches a maximum wind speed of 30 m/s. The annual average wind speed in this area is 6–7 m/s.

The field data used for this study are from seven wind farms in Muppandal, Tamilnadu, India, for a period from April 2002 to March 2005. The data covers 135 wind turbines with a total capacity of 37 MW from the seven wind farms and the details are given in Table 1. The data is intended to be typically representative of that of an Indian wind farm located in a region of high wind potential. The capacity of the selected wind farms ranges from 1 MW to 11.5 MW. Energy generation from each turbine, generation hours, machine maintenance and breakdown hours, grid maintenance and breakdown hours, wind speed and economic parameters are the main variables collected from these wind farms.

3. An overview of the definitions used for wind energy conversion system performance evaluation

3.1. Energy delivery factor

The key performance measure of any power plant is the electric energy it delivers over the year. The quantity of energy delivered depends on the rated power capacity of the plant and depends on how fully that capacity is utilized. The normalized measure of the wind power plant performance is the energy delivery factor (EDF) which is also called as capacity factor [7,8]. The energy delivery factor reflects how effectively the wind turbine could harness the energy available in the wind spectra. The annual energy delivery factor is given as:

$$\mathrm{EDF} = \int^{\text{year}} \frac{P_d(t)\,dt}{P_R \times 8760} \tag{1}$$

where P_R is the rated capacity of the wind turbine, $P_d(t)$ is the power delivered to the grid at any given time t.

In the present study, the energy delivery factor is analyzed on daily as well as monthly power generation from the seven wind farms. The wind generated power varies every instant and hence it is necessary to examine its reliable production for a utility industry, how much to be dependent on daily or monthly basis.

The energy delivery factor incorporates the energy conversion efficiencies of various components of the wind turbine and the availability of wind and wind turbines. From a study of the available data on the wind farms, it is seen that the wind farms considered for study operate at an average annual EDF of around 21%. It must be understood that the wind farm EDF varies with the season, having higher values during the windy period and lower values during less windy periods of the year. Fig. 1 shows wide variation in the energy generation, with EDF's ranging from 0.297% to 66.48% in a year.

3.2. Expected wind energy not supplied

The reliability of the wind power plant is evaluated by an index, coined for the purpose called expected wind energy not supplied (EWNS). This index gives the expected period during which the total generation capacity (taken in terms of daily or monthly energy delivery factor) not exceeding a given power level (taken in terms of annual energy delivery factor).

The EWNS is given by:

$$\mathrm{EWNS} = \sum_{i=1}^{n} P_i(\mathrm{EDF}_i < \mathrm{AEDF}) \tag{2}$$

where i is the time step, a day or a month, n is the number of days or month, EDF_i is the energy delivery factor in time period i, AEDF is the annual energy delivery factor and $P_i(\mathrm{EDF}_i < \mathrm{AEDF}_i)$ is the probability that the annual energy delivery factor exceeds the energy delivery factor in time period i.

3.3. Loss of load expectation

The reliability of wind energy conversion systems can be evaluated by the index, loss of load expectation (LOLE). LOLE is the

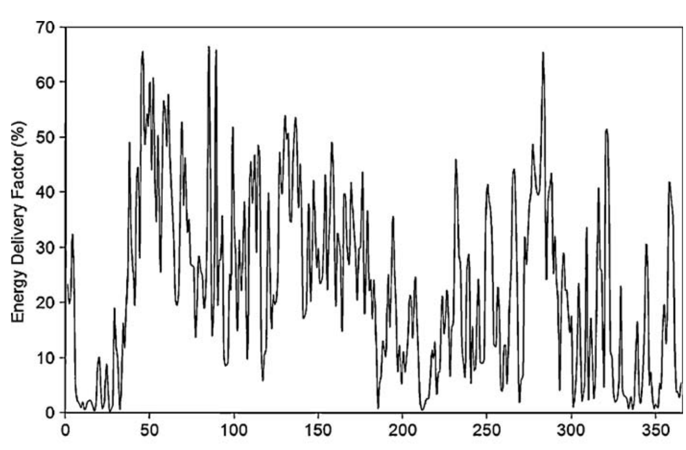

Fig. 1. Daily variation in energy delivery factor for a year indicating the fluctuating nature of wind energy.

Table 1
Capacity of wind farms taken for study.

Wind farms	WF1	WF2	WF3	WF4	WF5	WF6	WF7
Capacity (MW)	1.0	8.075	2.25	1.75	11.5	5.025	7.625

expected period during which the load demand exceeds the available generation capacity [9–13].

The LOLE is defined as:

$$\mathrm{LOLE} = \sum_{i=1}^{n} P_i(\mathrm{PG}_i < \mathrm{PD}_i) \quad (3)$$

where i is the time step, an hour or a day, n is the number of hours or days, PG_i is the power generation available in time period i, PD_i is the load demand in time period i and $P_i(\mathrm{PG}_i < \mathrm{PD}_i)$ is the probability that the load demand exceeds the available power generation in time period i.

3.4. Availability of a wind turbine

The 'availability' of a wind turbine refers to the percentage of time it is in a position or state for generating power. Servicing, inspection, component failures and accidents, such as lightning strokes reduce the availability of wind turbine. The availability of each wind turbine in a wind farm may differ depending on the net period of time for which it is functional in regard to power generation [14]. Grid breakdown and maintenance period are included in the calculation of availability factor since grid failure results in stalling of wind turbine. Data pertaining to the up and down times of the various turbines in the seven wind farms is used to estimate the availability that is given by Eq. (4). Fig. 2 shows the average availability of the seven wind farms.

$$\text{Availability } (\%) = \left[\frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}}\right] \times 100 \quad (4)$$

4. Reliability analysis of wind farms

4.1. Evaluation of expected wind energy not supplied

The reliability analysis is carried out for two cases. In the first case, the reliability evaluation is done with daily energy generation data and in the second case with monthly energy generation data. The capacities and annual energy delivery factor of the seven wind farms are given in Table 2. In the seven wind farms taken for study, wind farm WF6 shows the highest annual energy delivery factor of 25.9%. Even though the wind farms are sited in the nearby locations, the energy delivery factor differs in each wind farm. This may be due to site specific factors such as strength of wind spectra, machine efficiency. The study is extended to investigate the effect of increase in hub height of the existing wind turbine in the two cases.

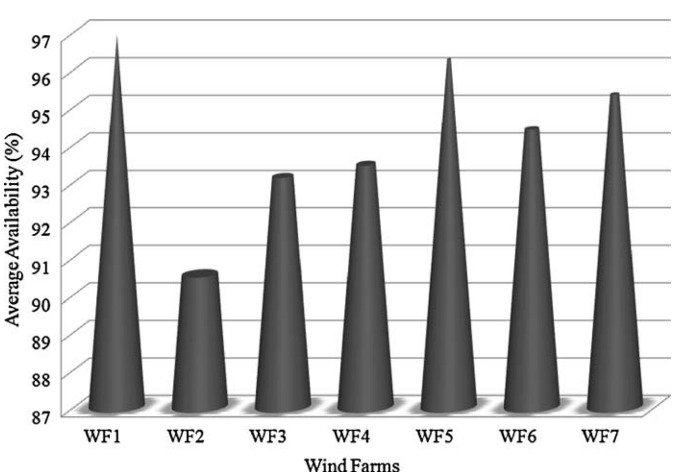

Fig. 2. Average availability of wind farms.

Table 2
Energy delivery factor of wind farms.

Wind farms	Capacity (MW)	Annual energy delivery factor (%)
WF1	1.0	21.3
WF2	8.075	15.0
WF3	2.25	15.7
WF4	1.75	23.1
WF5	11.5	25.2
WF6	5.025	25.9
WF7	7.625	21.2

Table 3
EWNS and reliability at different hub heights with daily generation data.

Increment in hub height	Reliability index (%)	
	EWNS (days/year)	Reliability (%)
0	191.5	47.55
2	182.5	50.00
4	174	52.33
6	164	55.06
8	153.5	57.95
10	147.5	59.59

Table 4
EWNS and reliability at different hub heights with monthly generation data.

Increment in hub height	EWNS (months/year)	Reliability (%)
0	6.9	42.2
2	6.8	43.5
4	6.6	45.3
6	6.1	49.1
8	5.3	56.1
10	4.9	59.2

For the first case, the number of days the expected wind energy not supplied is evaluated and is given in Table 3. The results obtained show that the expected wind energy not supplied in a year is 191.5 days and a wind energy conversion system is 47.55% reliable in meeting the expected wind energy.

To enhance the reliability of wind power plant, it is necessary to improve the overall performance of the plant. The reliability index can be improved if the amount of energy generation increases. A change of many parameters in an existing wind farm may not be cost effective. Therefore, the analysis is carried out by increasing the hub height of the existing wind turbine which increases the power generation. As the hub height increases the rotor blades are exposed to higher wind speeds, since the wind speed increases with altitude. The average wind speed measured at a given height is related to the average wind speed measured at another height in the same vertical plane and is given as [15]:

$$\frac{V(h)}{V(h_r)} = \left[\frac{h}{h_r}\right]^{\alpha} \quad (5)$$

where $V(h)$ is the wind speed at the height h, $V(h_r)$ is the wind speed at the reference height, h_r and α is the power law exponent and is taken as 0.3. The exponent α is an empirically derived coefficient that varies with parameters such as surface roughness, wind speed, temperature [15]. Assuming that there is no variation in air density and the blade diameter, the power generation at given height, $P(h)$, can be expressed as

$$P(h) = P(h_r)\left[\frac{h}{h_r}\right]^{3\alpha} \quad (6)$$

where $P(h_r)$, is the power generation at the reference height.

The hub height of the wind turbines in the wind farm is incremented in steps of 2 m for simulations. The obtained

Table 5
EWNS and reliability of each wind farm at different hub heights with monthly generation data.

Increm at in hub height	0 m		2 m		4 m		6 m		8 m		10 m	
Wind farms	EWNS	*R* (%)	EWNS	*R* (%)	EWNS	*R* (%)	EWNS	*R* (%)	EWNS	*R* (%)	EWNS	*R* (%)
WF1	6.5	45.70	6.2	48.40	5.8	51.40	4.9	59.60	4.2	64.90	3.9	66.80
WF2	7.1	41.66	7.1	41.52	7.0	41.40	7.0	41.28	7.0	41.04	6.9	42.82
WF3	7.3	39.60	7.2	39.80	7.2	40.30	7.0	41.00	6.8	43.00	6.7	43.90
WF4	7.1	41.16	7.0	41.52	7.0	41.66	6.9	41.84	6.9	42.22	6.9	42.88
WF5	7.1	40.50	6.9	41.90	6.3	47.70	6.1	49.60	5.9	50.10	4.9	58.90
WF6	6.5	45.90	5.8	52.00	5.6	53.10	5.4	54.80	5.1	57.40	5.1	58.00
WF7	6.2	48.28	5.4	54.68	5.3	55.60	5.3	55.56	4.4	63.48	4.2	65.10

Table 6
EWNS and reliability of each wind farm for three year period with monthly generation data.

Wind farms	Base hub height					
	2002–2003		2003–2004		2004–2005	
	EWNS	Reliability (%)	EWNS	Reliability	EWNS	Reliability (%)
WF1	6.9	42.2	6.5	46.2	6.3	47.36
WF2	6.9	42.46	7.1	41.14	5.9	50.75
WF3	6.9	42.5	6.9	41.98	5.9	50.87
WF4	6.4	46.7	7.1	40.9	6.1	49.15
WF5	7.0	41.8	7.0	41.96	7.1	41.38
WF6	6.2	48	6.8	43.04	6.9	42.2
WF7	7.2	39.92	4.9	59.16	6.4	46.72

reliability index is given in Table 3. The increase in hub height shows that the reliability index, EWNS decreases in each step, thus representing an improvement in reliability. The analysis shows that the reliability improves to an average of 12.04% with increase in hub height of 10 m.

In the second case, the number of months the expected wind energy not supplied is evaluated. The results obtained show that at the base hub height, the expected wind energy not supplied in a year is 6.9 months and a wind energy conversion system is 42.2% reliable in meeting the expected wind energy. The increment in the hub height analysis is also carried out with monthly generation data. Table 4 gives the reliability index at different hub heights. Tables 5 and 6 give the EWNS index obtained for all the seven wind farms separately and the EWNS index for the three years for which the data are collected.

Table 7
LOLE index and reliability at the base hub height and increment in hub height.

Hub height	Percentage of installed capacity as max. load demand (%)	LOLE (hours/year)	Reliability (%)
At the base hub height	40	261.8	9.11
	35	235.5	18.21
	30	212.0	26.39
	25	181.3	37.07
	20	134.5	53.29
Increase in hub height by 10 m	40	219.2	23.88
	35	198.6	31.06
	30	170.7	40.73
	25	130.5	54.68
	20	85.1	70.46

4.2. Evaluation of expected wind energy not supplied

The chronological hourly generation data for each month of the wind farms is compared with load demand of a chronological hourly load demand model. The total installed capacity of the seven wind farms from which the data are collected is 37 MW. The maximum hourly average power generation from these seven wind farms is 15 MW, which is 40% of the installed capacity. This power generation is somewhat low in comparison with the rated wind farm capacity, mainly due to the stochastic nature of wind, availability of wind turbines and grid etc.

4.2.1. Load demand curve

For the reliability estimation, information of the load curve is essential. Since the wind farms are located in Muppandal in the state of Tamilnadu and feed the state grid, it is appropriate to apply the analysis to the load demand curve for the state grid. The actual state grid is supplied with power from sources of generation other than wind power. Hence, to isolate the contribution/impact of the wind farms alone, it became necessary to scale down the state grid such that the peak demand of the grid corresponds to that associated with the wind farms. The load curve as applied to the evaluation of the reliability of wind farms therefore is derived by scaling down the actual load demand curve pattern. The peak load demand is taken as 15 MW, which is equal to the maximum hourly average power generation. The obtained load curve for the study is of the similar trends of the state grid load curve, but with magnitude reduction. Fig. 3 shows the load curve for the reliability

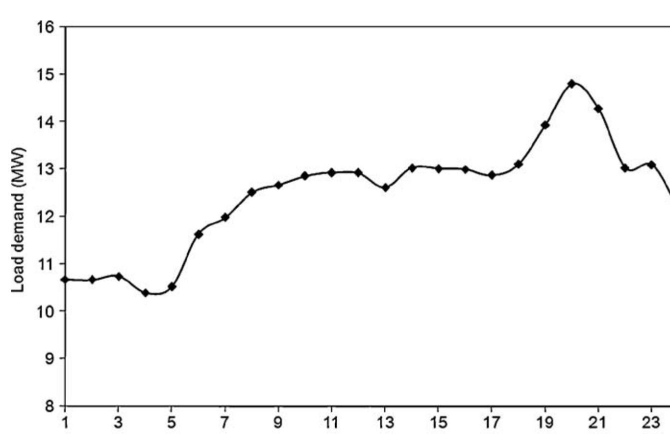

Fig. 3. Scaled down load curve pattern used for reliability evaluation.

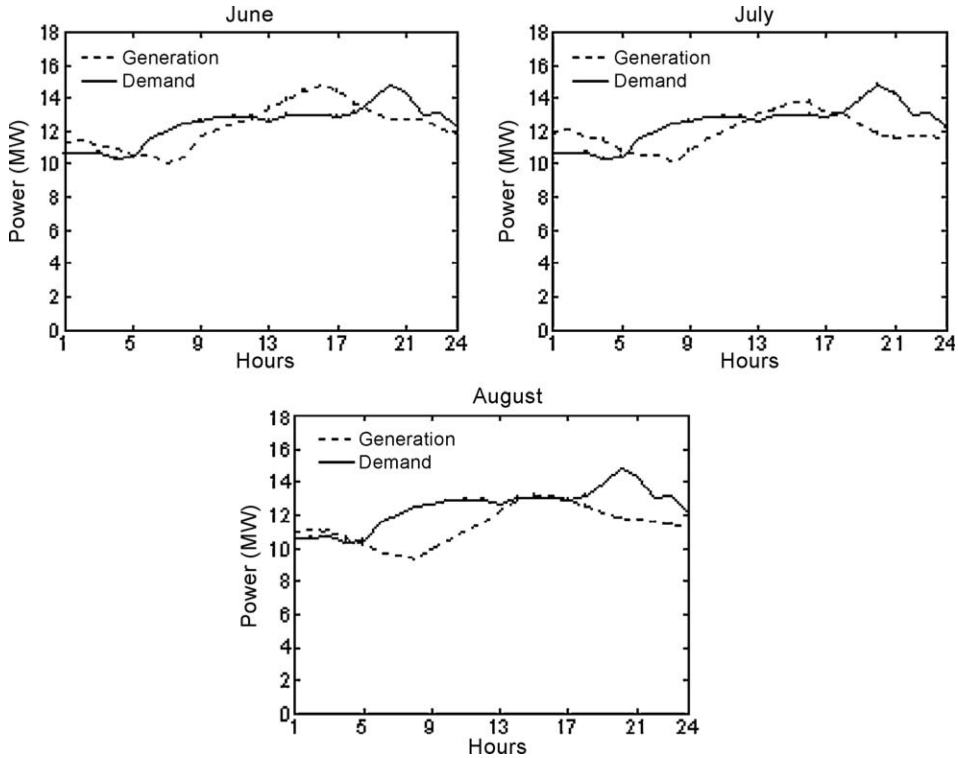

Fig. 4. Profiles of the wind farm power generation and the load demand when the peak demand is assumed as 15 MW.

evaluation. The LOLE index is obtained by comparing hourly average generation of each month with the corresponding hourly load demand.

4.2.2. Analysis

Table 7 shows the LOLE in hours per year and the reliability in percentage. The percentage reliability (R) is calculated as given below:

$$\text{Reliability}\ (\%) = \left[\frac{\text{No. of hours} - \text{LOLE}}{\text{No. of hours}}\right] \times 100 \qquad (7)$$

When the peak load demand is assumed equal to the maximum hourly average power generation, which is 40% of the total

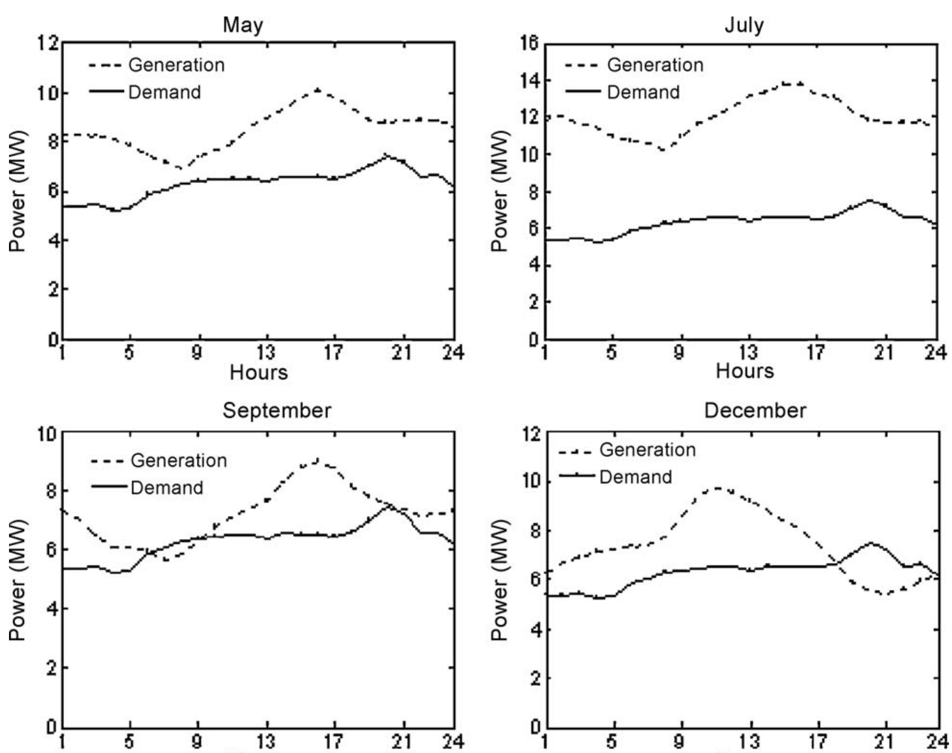

Fig. 5. Profiles of the wind farm power generation and the load demand when the peak demand is assumed as 7.5 MW.

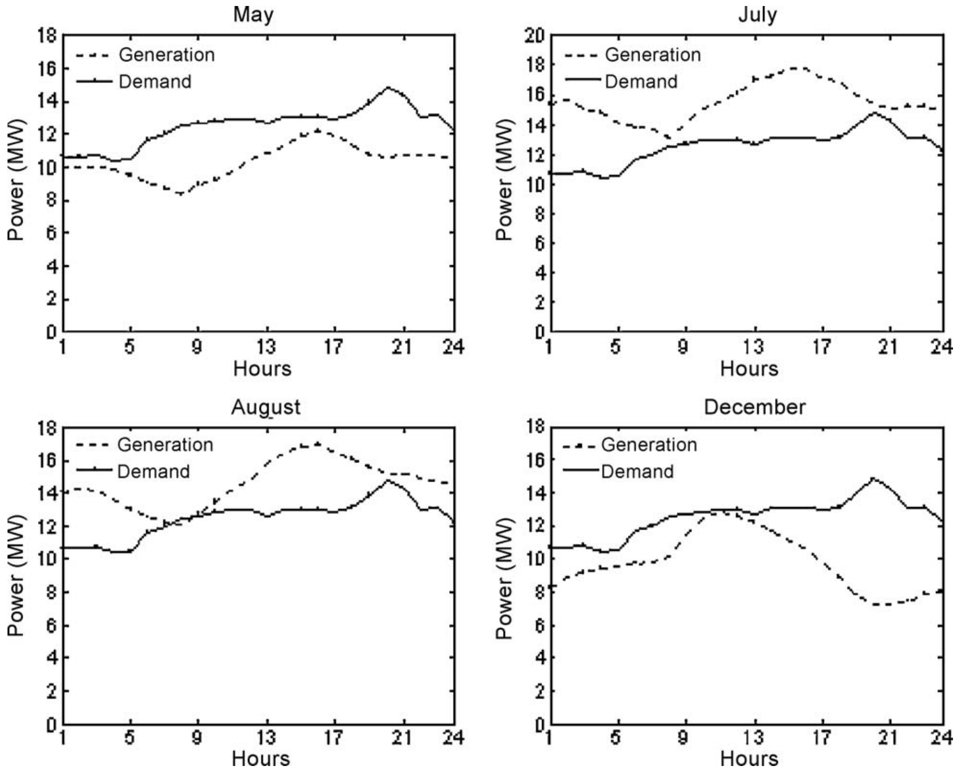

Fig. 6. Profiles of the wind farm power generation and the load demand when the peak demand is assumed as 15 MW and with hub height increment of 10 m.

installed wind power capacity; the loss of load expectation index is obtained as 261.77 h/year. This means the wind farm reliability contribution is 9.11% in meeting the load demand. A very low value of percentage reliability is obtained, because the hourly power generation is higher than the demand only for a few hours in the months of June, July and August. This is shown in Fig. 4. The analysis is done further by scaling down the load demand profile to achieve 50% reliability in meeting the load demand. Hence the peak load demand is decreased by 5% in each step. The LOLE index and the corresponding percentage reliability are shown in Table 7.

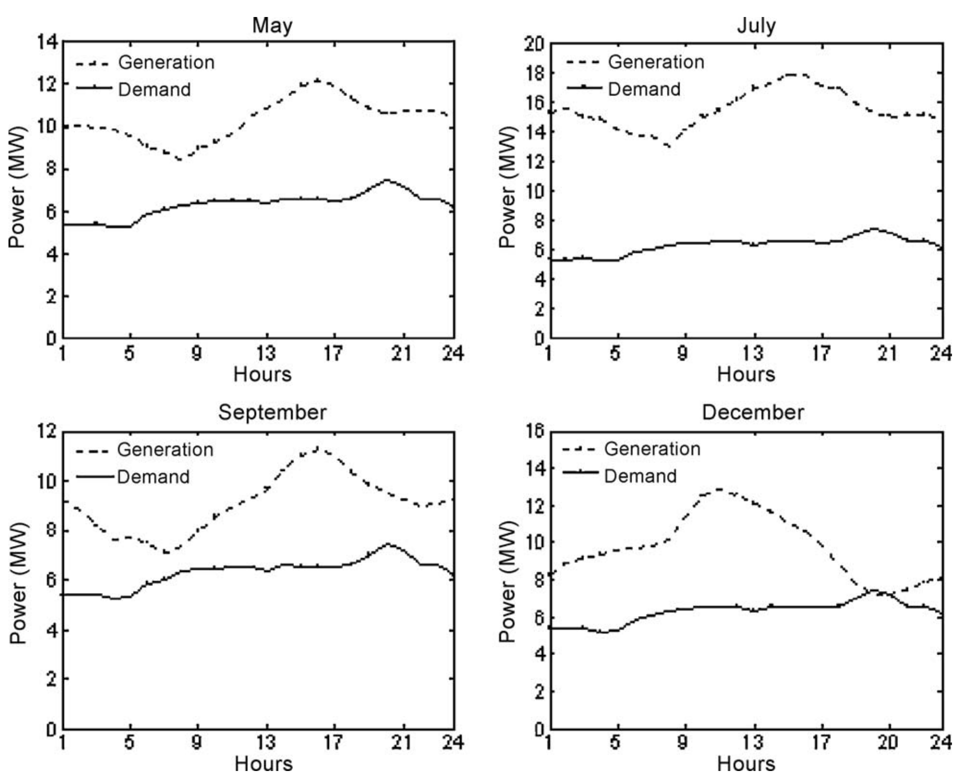

Fig. 7. Profiles of the wind farm power generation and the load demand when the peak demand is assumed as 7.5 MW and with hub height increment of 10 m.

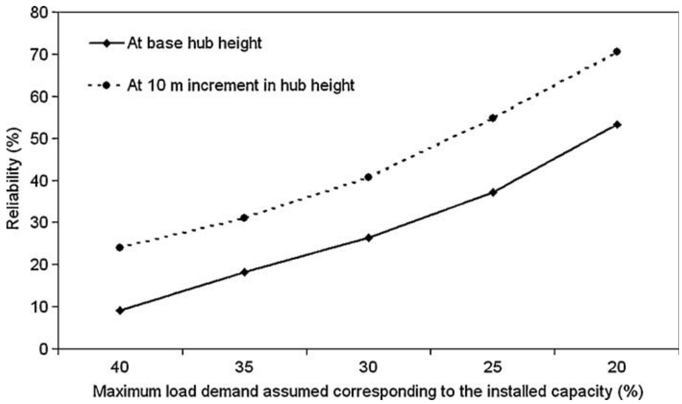

Fig. 8. Reliability of wind farms in meeting the load demand at base height and at 10 m increment in hub height.

When the peak load demand is 20% of the total wind power capacity, the reliability of 53.29% is obtained. The profiles of wind power generation and load demand at 20% of the total wind power capacity May, July, September and December are shown in Fig. 5.

It can be seen from Fig. 4, how the hourly, monthly and seasonal variation of wind speed affects the wind power generation and thereby its reliability. The highest wind power system performance is during the month of June, July and August. It is noted that throughout the year, a base power generation of 5.5% of the total wind power capacity is available from the wind farms. Another feature of wind energy to be noted from this study is that during off peak hours in demand, the wind power generation is high and during peak hours the wind power generation is low. The wind power generation is higher than or equal to the load demand for certain period of the day, but the time of the day does not match with the demand and so the demand is not met effectively. This signifies that the wind energy must be considered only for meeting part of the base load while integrating with the conventional systems. The analysis also shows the hours during which the power generation is high and low, and accordingly the energy planners must handle the reserves in power system.

In case of stand-alone or hybrid systems, the analysis signifies the role of storage systems. The energy surplus can be stored in batteries or other means, in order to be used during time of insufficient wind energy production or sold to the utility or for other purposes. Reserved energy in storage systems can be instantaneously used as back-up, if the energy supply is significantly reduced by the random changes in wind speed. In addition, the storage can also help to reduce the utility of other sources for peak hour's requirements by storing energy in times of low demand and using it in peak hours.

The improvement in reliability by increasing the hub height of wind energy conversion system by 10 m is investigated. The relationship between the hub height and wind speed is given in Eq. (5). The results are presented in Table 7. Figs. 6 and 7 show the comparison of wind power generation at increased hub height of 10 m and load demand for the months of May, July, September and December, when the peak load demand is assumed as 40% and 20% of the total installed wind power capacity. The LOLE index decrease as the hub height is increased, thus showing improvement in the reliability. Fig. 8 shows the reliability curves with base hub height and 10 m increment in hub height.

5. Conclusions

It is important that a power system should provide a reliable electric power to the consumers. Determination of appropriate generating sources is essential to meet the expected total demand. While operating wind energy conversion systems with the other sources, it is necessary to know when and how much power will be available from wind in order to satisfy the load demand. This evaluation study is helpful to energy planners and operators in planning and decision-making.

A wind energy conversion system does not represent an equivalent amount of its existing installation capacity. With the index of EWNS, an analysis is carried out for the study of reliability performance of wind energy conversion systems in meeting the annual energy delivery factor. The reliability contributions with daily and monthly generation data are obtained as 47.55% and 42.2% respectively to meet the annual EDF. The study also reveals that hub height is positively correlated to improved wind power plant reliability.

With the evaluation of LOLE, it is seen that the reliability contribution of wind farms is 53.29% when the peak load demand is assumed as 20% of the installed wind power capacity. It is found that there is no matching of peak load period with the maximum wind power generation period. However, the total energy contribution by the wind farms to the power system is significant. Therefore in a power system, wind generated power, if available, must be utilized to the maximum to meet the base load demands and thereby conserve conventional fuels and to reduce emissions.

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